Downloaded from orbit.dtu.dk on: May 05, 2023

DTU Library

High-LET dose-response characteristics described by track structure theory of heavy charged particles

Hansen, J.W.; Olsen, K.J.

Publication date:
1981

Document Version
Publisher's PDF, also known as Version of record

Link back to DTU Orbit

Citation (APA):
Hansen, J. W., & Olsen, K. J. (1981). *High-LET dose-response characteristics described by track structure theory of heavy charged particles*. Risø National Laboratory. Risø-M No. 2308

General rights
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

RISØ-M-2308

HIGH-LET DOSE-RESPONSE CHARACTERISTICS DESCRIBED BY TRACK STRUCTURE THEORY OF HEAVY CHARGED PARTICLES.

Johnny W. Hansen and Kjeld J. Olsen

Abstract. The track structure theory developed by Katz and co-workers ascribes the effect of high-LET radiation to the highly inhomogeneous dose distribution due to low energy δ-rays ejected from the particle track. The theory predicts the effectiveness of high-LET radiation by using the ion parameters z_{eff}, effective charge of the ion, and $\beta = v/c$, the relative ion velocity, together with the characteristic dose D_{37} derived from low-LET dose-response characteristic of the detector and the approximate size a_o of the sensitive element of the detector. ^{60}Co gamma-irradiation is used as a reference low-LET radiation, while high-LET radiation ranging from 16 MeV protons to 4 MeV/amu ^{16}O-ions covering an initial LET range of 30-5500 MeVcm^2/g is obtained from a tandem Van de Graaff accelerator.

(Continue on next page)

September 1981
Risø National Laboratory, DK 4000 Roskilde, Denmark

A thin film (5 mg/cm^2) radiochromic dye cyanide plastic dosemeter was used as detector with the characteristic dose of 16.8 Mrad and a sensitive element size of 10^{-7} cm.

Theoretical and experimental effectiveness, RBE, agreed within 10 to 25% depending on LET.

INIS-descriptors: COLORIMETRIC DOSEMETERS, CYANIDES, DOSE-RESPONSE RELATIONSHIPS, DYES, IONIZING RADIATIONS, LET, PARTICLE TRACKS, RADIATION DETECTORS.

UDC 539.1.074

This work has been presented at the 7th Danish-Polish Symposium on Radiation Chemistry, Risø, 7-10 September 1981.

ISBN 87-550-0788-0
ISSN 0418-6435

Risø Repro 1981

CONTENTS

1. INTRODUCTION

It is a well-known fact that the dose-response of both physical and biological detectors varies with LET, the linear energy transfer of the incoming charged particle. For biological systems as for physical detectors the effect of high-LET radiation relative to low-LET radiation may be both larger and smaller than one, while most physical detectors display a monotonic decline in relative effect for an increase in LET.

At the moment there are essentially only two theories attempting to explain these results. One is the two-component theory or α-β model of Rossi and Kellerer, ref. 1, and the second is the particle track structure theory or δ-ray theory of Katz and coworkers, ref. 2. While the first theory fails at very high LET values and is a very poor predictor of the detector response, the model of track structure covers all LET-values and is predictive for many detector systems. We have at Risø examined the track structure theory and compared experimental and theoretical dose-response characteristics for a polymer detector, a thin film dosemeter, and we have found excellent agreement.

2. CONCEPTUAL THEORY

The track structure theory derives from the observation that track effects in different detector systems indicate, that secondary and higher order generation electrons, called δ-rays, ejected from the path of an energetic ion are responsible for the radiation effects. Radiation effects from other types of radiation, e.g. X-rays, and high energy electrons, are also mediated through low energy electrons. The importance of the low energy electrons has been emphasized by Paretzke, ref. 3, who suggested that electrons of energy around and below 1 keV will be most effective in producing radiation effects, since at this energy the ionization cross-section will be sufficient large and the energy so high that 5-10 ionizations will occur within a small volume. The conclusions have been supported by the findings of Goodhead, ref. 4, in a study of biological effects of super-soft X-rays.

The track theory takes the above into account by proposing that the difference in effect between low- and high-LET radiation is due to the highly inhomogeneous dose distributions and that the response of a physical detector to high-LET radiation can be calculated from parameters of low-LET radiation.

We have concentrated on the dye film dosemeter which is considered as a one-hit detector and the response of which to both low- and high-LET radiation may be described by Poisson statistics such that the probability for activation of a radiation sensitive element is

$$P(z,\beta,t,a_0) = 1- \exp(-\bar{D}(z,\beta,t,a_0)/D_{37})$$

where z = the effective charge : the moving ion, β = the ion velocity relative to the velocity of light, t = the distance from the ions' path, a_0 = radius of the sensitive element, $\bar{D}$ = the average dose to the sensitive element, and D_{37} = a characteristic dose at which there is an average of one-hit per sensitive element (Fig. 1). In a one-hit detector the sensitive elements cannot accumulate sublethal damage, and the activation proceeds from the passage of a single electron or ion through the sensitive element.

In this theory of track structure only electromagnetic interactions with photons or with charged particles are taken into account, whereas effects responding from nuclear interactions are assumed to be negligible. Further, the theory does not incorporate fading, bleaching, or dose-rate effects which additionally must be taken into consideration.

The assumptions and approximations necessary for evaluating the dose-response characteristic for a detector when irradiated with high-LET radiation are briefly outlined in the following.

The detector is assumed to be made up of sensitive elements in the shape of cylinders with radius a_0, where the axis is parallel to and positioned at a distance t to the ion's path. Though different parts of the cylinder experience different doses in the strongly varying field around the ion's path, the dose response is determined by the average dose delivered to the element. The dose profile around the ion's path is calculated from the Bethe-Bloch energy distribution formulation for δ-rays and a simplified stopping power formalism for low-energy electrons. Without going into details the formula for calculating the dose profile can be expressed as

Point target: $$D_\delta(t) = \frac{1}{2\pi t\,dt}\int_{\omega_t}^{\omega_{max}} \frac{dn(\omega_r)}{d\omega_r}\frac{d\omega_{r\text{-}t}}{dt}\,d\omega_r\,dt$$

Extended target: $$\bar{D}(t) = \frac{1}{\pi a_0^2}\int_{t-a_0}^{t+a_0} D_\delta(t)\cdot A(a_0,t)\,dt$$

where $(2\pi t dt)^{-1}$ = volume element per unit length, $\frac{dn(\omega_r)}{d\omega_r}$ = δ-ray energy distribution, $\frac{d\omega_{r-t}}{dt}$ = electronic stopping power, and $A(a_0,t)$ = geometry function.

The Bethe-Bloch equation is not valid at very low energies where binding effects play a role in determining the energy spectrum. This problem is partly avoided by considering an area of radius a_0 and with the center at the ion's path separately from the rest of the detector. The total energy of the δ-rays with energy large enough to have ranges larger than a_0 is calculated. The energy deposited in the central element can then be calculated from a subtraction of the energy deposited in the track by the δ-rays outside the central core from the total energy deposited by the moving ion. The calculated extended target dose $\bar{D}$ as a function of the distance t to the ion's path is shown in Fig. 2.

At this point of the calculation the shape of the dose-response characteristic after gamma irradiation has an important implication for the response to high-LET radiation. The dose-effect relationship found after gamma-irradiation serves to translate the radial distribution in local dose from the δ-rays ejected from a medium by a single passing ion into a radial distribution in probability for activation. In order to consider the total effect from the ion on targets at all distances from the ions' path, an integration of the probabilities must be made over the detector volume being affected by the δ-rays generated by the ion. This integration yields the total activation cross-section σ_T and is calculated from

$$\sigma_T(z,\beta,a_o) = 2\pi\int_0^{t_{max}} P(z,\beta,t,a_o)\,t\,dt$$

where t_{max} is the maximum range of the most energetic δ-rays.

The radiosensitivity of a detector to heavy-ions is defined as σ_T/E_T, where E_T is the total energy deposited by the ion, and the radiosensitivity of a detector to low-LET radiation, e.g. gamma-rays, is given by $1/D_{37}$. The relative effectiveness of a detector or the RBE, relative biological effectiveness, is defined by the ratio between the radiosensitivities for heavy ions and low-LET radiation and can be expressed as $RBE = \sigma_T \cdot D_{37}/E_T$. E_T can be expressed as LET of the stopping ion. Figure 3 shows RBE as a function of z_{eff}^2/β^2 in a track segment calculation of an oxygen ion in the dye film. Plotting RBE as a function of LET for different ions no smooth relationship occurs, whereas the use of z_{eff}^2/β^2, which has the same dimension as LET, gives a relationship in accordance with experimental findings.

In case of a thick detector compared to the range of the ions it is necessary to perform the calculation in segments. The cross-section and effectiveness are calculated for each segment, and the effectiveness averaged with respect to the energy deposited in each segment.

3. EXPERIMENTAL AND DISCUSSION

The radiation detector used in these experiments is a thin-film (5 mg/cm^2) plastic dosemeter developed for measurements of high absorbed doses and dose distribution in intense radiation fields, ref. 5. The radiation sensitive element is the leuco dye molecule, the size of which is about 10 Angstrom and so giving an a_0 of $0.5 \cdot 10^{-7}$ cm. The characteristic gamma-ray dose at which theoretically 63% of the leuco dye molecules are converted to the coloured dye molecules is found from the measured dose-response curve for ^{60}Co gamma-rays (Fig. 1). 63% of the saturation optical density occurs at a D_{37} dose of 16.8 Mrad.

The radiation dose-response curve for the film compared to the response of an ideal one-hit detector shows a slope following a less steep response (Fig. 1). Further, when irradiating the film to very high doses the response bends over and a strong bleaching effect takes place. As the detector in principle is a one-hit detector, an explanation for the sublinear response could be that the bleaching effect always is present even at low doses. Another disagreement with an ideal detector is the varying saturation optical density with radiation quality, a variation which seems to be connected to dose rate. Comparing the dose-response characteristic for the different radiation qualities (Fig. 4), the slope of the curves for ΔOD/mm less than 20 is the same in a double logarithmic plot indicating the same influence from the bleaching effect in the low dose region.

Hence the bleaching effect must be regarded as a competitive reaction to the formation of the coloured dye molecules, and we are dealing with two simultaneous effects, whereas theory only takes one effect into consideration. The bleaching effect, however, has a negligible influence on the determination of the relative effectiveness, which can be derived either from the parallel displacement of the curves in a double logarithmic plot, (Fig. 4), or from the initial slope of the dose response characteristics in a linear plot (Fig. 5). A prediction of the radiation sensitivity of the detector film for any other radiation quality will be possible as long as we are dealing with doses causing a ΔOD/mm of less than 20. A prediction of the saturation optical density is by now impossible, but work is in progress of investigating the mechanism controlling the bleaching effect and of including a competitive effect into the model.

Figure 5 shows the dose-response characteristics at low doses of the radiation qualities under investigation, namely ^{60}Co gamma-ray photons, 16 MeV protons, 10 MeV α-particles, 3 MeV/amu ^{7}Li-ions, 3 MeV/amu ^{14}N-ions, and 4 MeV/amu ^{16}O-ions. The dose-response characteristics for the ions show a less steep response than the one for gamma-rays indicating a decrease in relative effectiveness and thus a RBE less than one. The theoretically and experimentally obtained values of RBE and the corresponding initial LET and average z^2_{eff}/β^2 values, as shown in Table 1, indicate qualitatively excellent agreement. The disagreement of about 25% at the high-LET values could be ascribed to the strong bleaching effect in the central core of the ions' track, or at the same time a dosimetric problem as a fluence measurement based on integrated charge is a difficult task for heavy ions.

In the concept of the calculated track profiles shown in Fig. 2 the effectiveness of an ion can be explained by the position of an imaginary horizontal line drawn at a value of $\bar{D}$ equal to D_{37} relative to the profile for the actual ion. If the line lies above the plateau of the profile, the ratio $\bar{D}/D_{37}$ is less than one for all sensitive elements affected by the ion including those through which the ion passes, and the RBE equals one. If the horizontal line lies below the plateau of the actual curve, the ratio $\bar{D}/D_{37}$ is bigger than one in a certain part of the track and all sensitive elements at distances several times a_0 from the ions' path will be fully activated. A waste of energy takes place and the RBE is smaller than one.

Although the dose to the core for the protons is less than the D_{37} value, the dose is in the saturating region causing an effectiveness a little less than unity. The saturation sets in for values of $\bar{D}$ approaching the characteristic dose D_{37}. The effectiveness of the ions shows a rapid decrease once the dose to the central core exceeds D_{37}. But as the saturation region only expands slowly with increasing LET, a slow decrease in RBE is observed at very high LET-values, Fig. 3.

4. CONCLUSION

From this study we can conclude that it is possible quantitatively to predict the dose-response characteristics for high-LET particles in a one-hit detector by means of the theory of track structure, a measured dose-response characteristic for low-LET radiation, and the knowledge of the approximate size of the sensitive element. More exact theoretical values may, however, be obtained by including in the track structure model the influence from a competitive action on the formation of observed effect.

ACKNOWLEDGEMENT

The authors are indebted to The Niels Bohr Institute, Risø, for providing irradiation time at the Van de Graaff tandem accelerator, and to M. Wille for his skilful help in construction of the experimental equipment and read-out of the irradiated film samples.

REFERENCES

1. Kellerer, A.M., Rossi, H.H., "RBE and the Primary Mechanism of Radiation Action". Radiation Research 47 (1971) 15-34.

2. Katz, R., Sharma, S.C., Homayoonfar, M, "The Structure of Particle Tracks", in Topics of Radiation Dosimetry, Supplement 1. Edited by F.H. Attix, Academic Press, New York, London (1972) 317.

3. Frankenberg, D., Frankenberg-Schwager, M., Grundler, W., Krüger, E.H., Paretzke, H.G., Pohlit, W., Rimpl, G., "Radiation Studies at the Physical, Molecular, Cellular and Macrocolony Level". Sixth Symp. on Microdosimetry, 22-26 May 1978, Vol. I, p 121, Brussels, Belgium.

4. Goodhead, D.T., Cox, R., Thacker, J. "Do Ultrasoft X-rays Produce Lesions Characteristic of High-LET or Low-LET or Neither?". Seventh Symp. on Microdosimetry, 8-12 Sept. 1980, Oxford, England, Vol II, p 929.

5. McLaughlin, W.L. et al., "Radiochromic Plastic Films for Accurate Measurement of Radiation Absorbed Dose and Dose Distributions". Rad. Phys. Chem. 10 (1977) 119-127.

Table 1.

Type of radiation	β_{init}	LET_{init}	LET_{av}	z^2_{eff}/β^2_{av}	RBE_{th}	RBE_{exp}
^{60}Co γ-rays					1	1
16 MeV protons	0.1853	31.4	31.5	29	0.95	0.94
10 MeV α-particles	0.0733	564	690	923	0.60	0.53
3 MeV/amu ^{7}Li-ions	0.0802	1079	1275	1660	0.56	0.48
4 MeV/amu ^{16}O-ions	0.0927	5227	7210	8981	0.46	0.35
3 MeV/amu ^{14}N-ions	0.0802	5496	6658	9962	0.41	0.30

LET and z^2_{eff}/β^2 have dimension of $MeVcm^2/g$.

LIST OF FIGURES

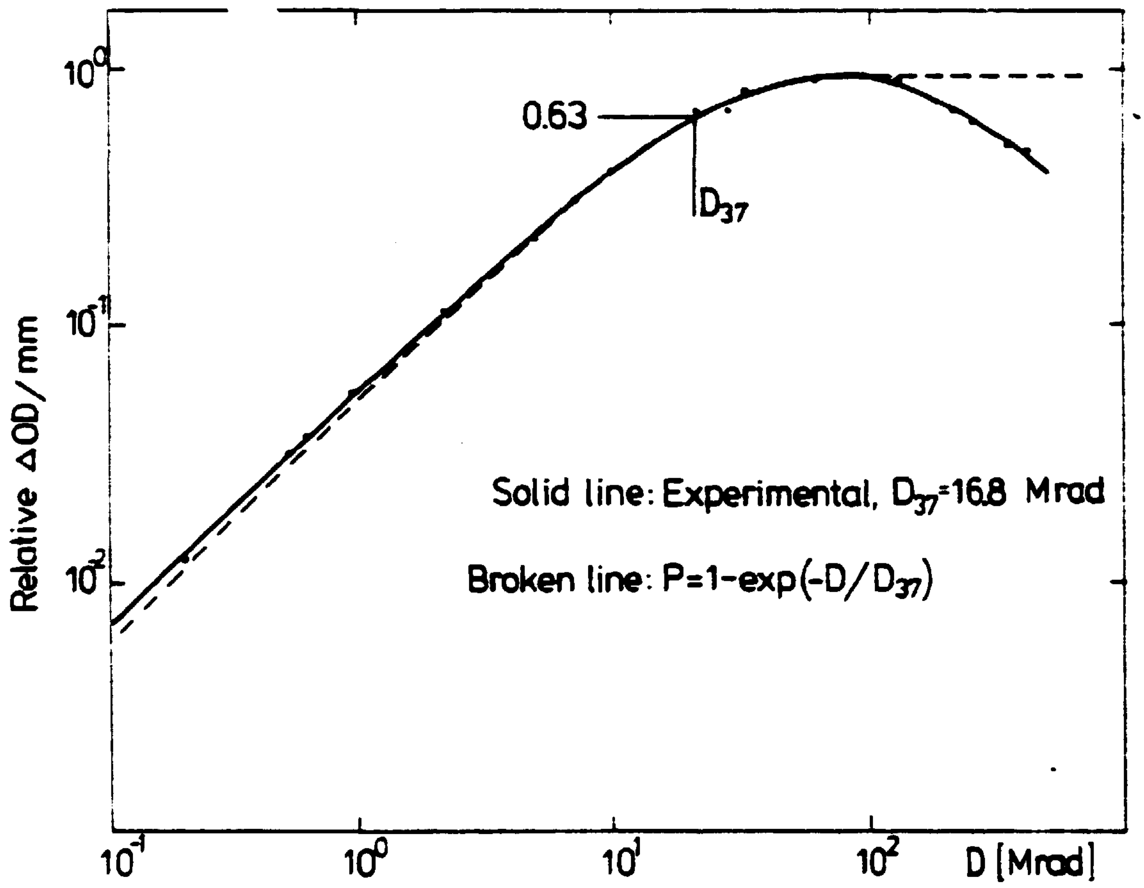

Fig. 1. Probability for activation of a one-hit detector $P(z,\beta,t,a_0) = 1 - \exp(-\bar{D}(z,\beta,t,a_0)/D_{37})$, broken line. Normalized ^{60}Co γ-ray dose response characteristic for the thin-film detector, solid line.

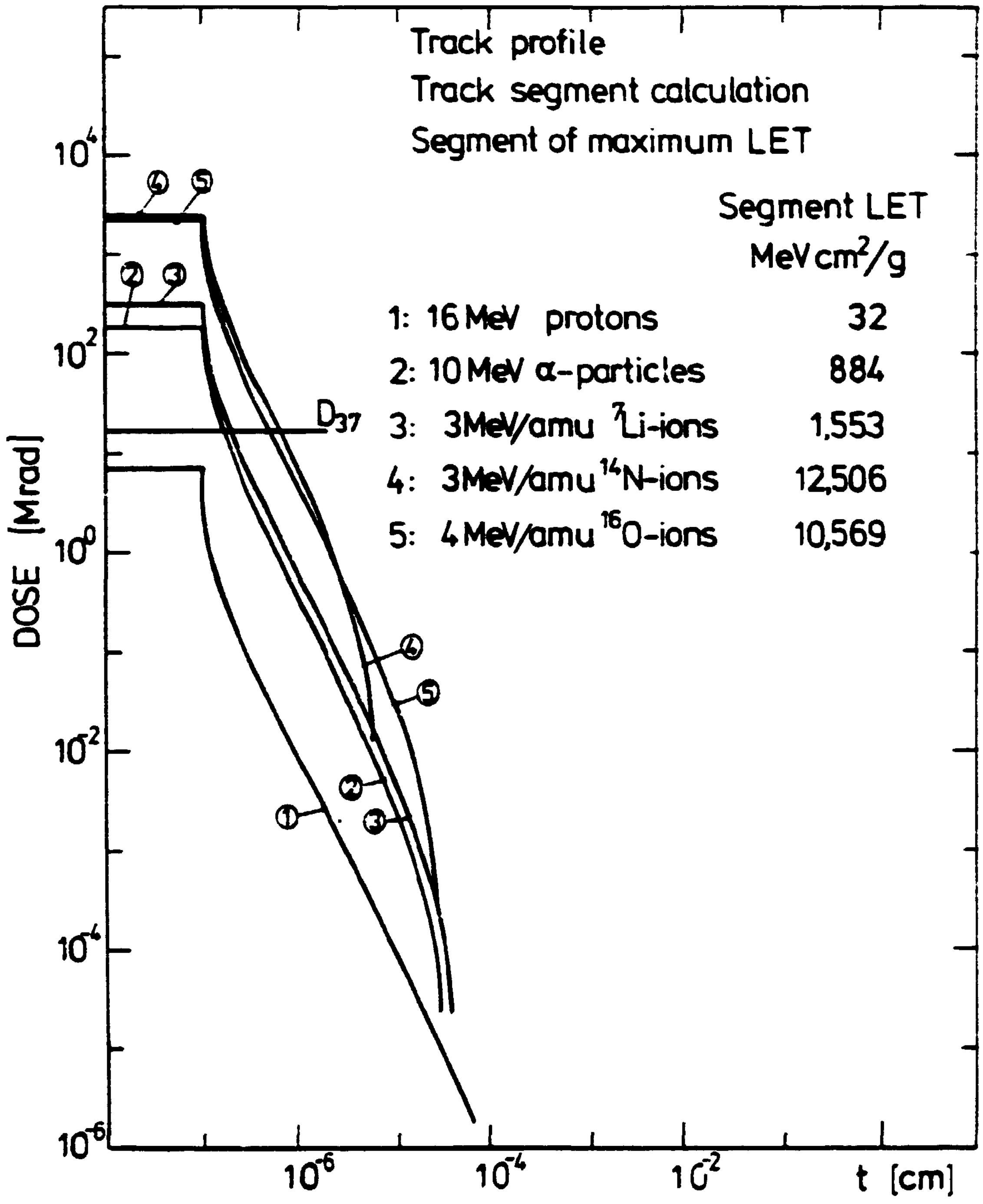

Fig. 2. Calculated extended target dose distribution around the path of the ion in a track segment. The profiles show the average dose deposited in a sensitive element of radius $a_0 = 10^{-7}$ cm.

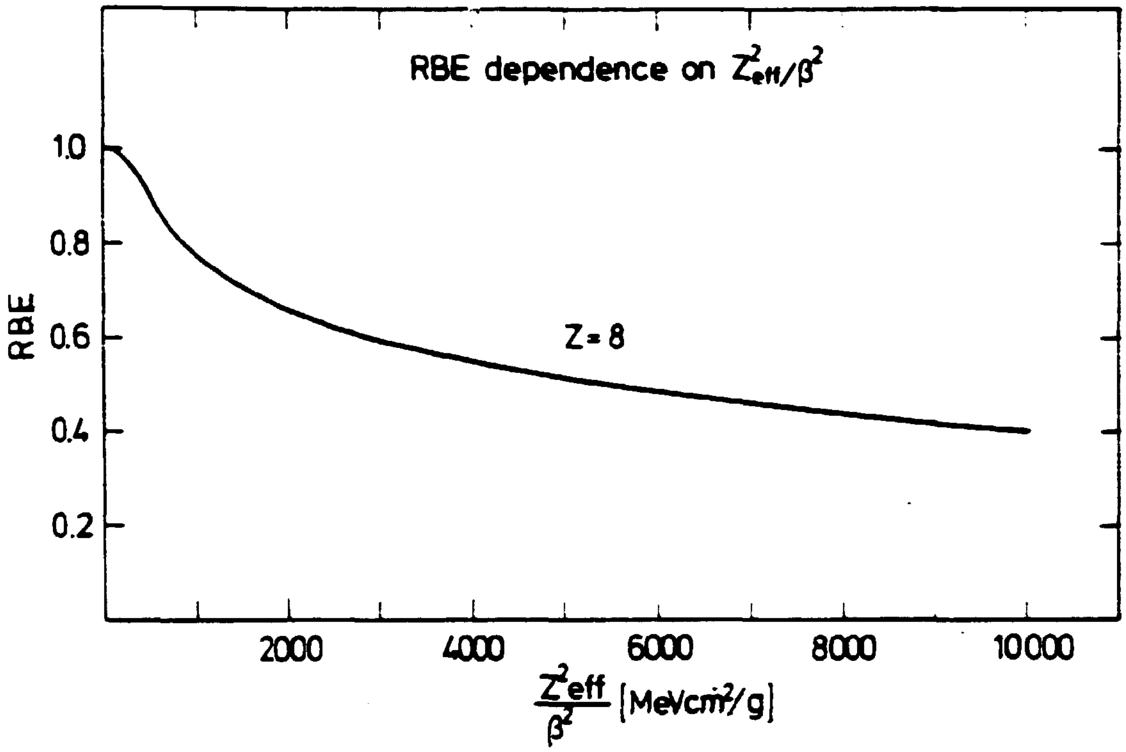

Fig. 3. Relative biological effectiveness, RBE, as a function of z^2_{eff}/β^2 in a track segment calculation of an oxygen ion in the thin-film detector.

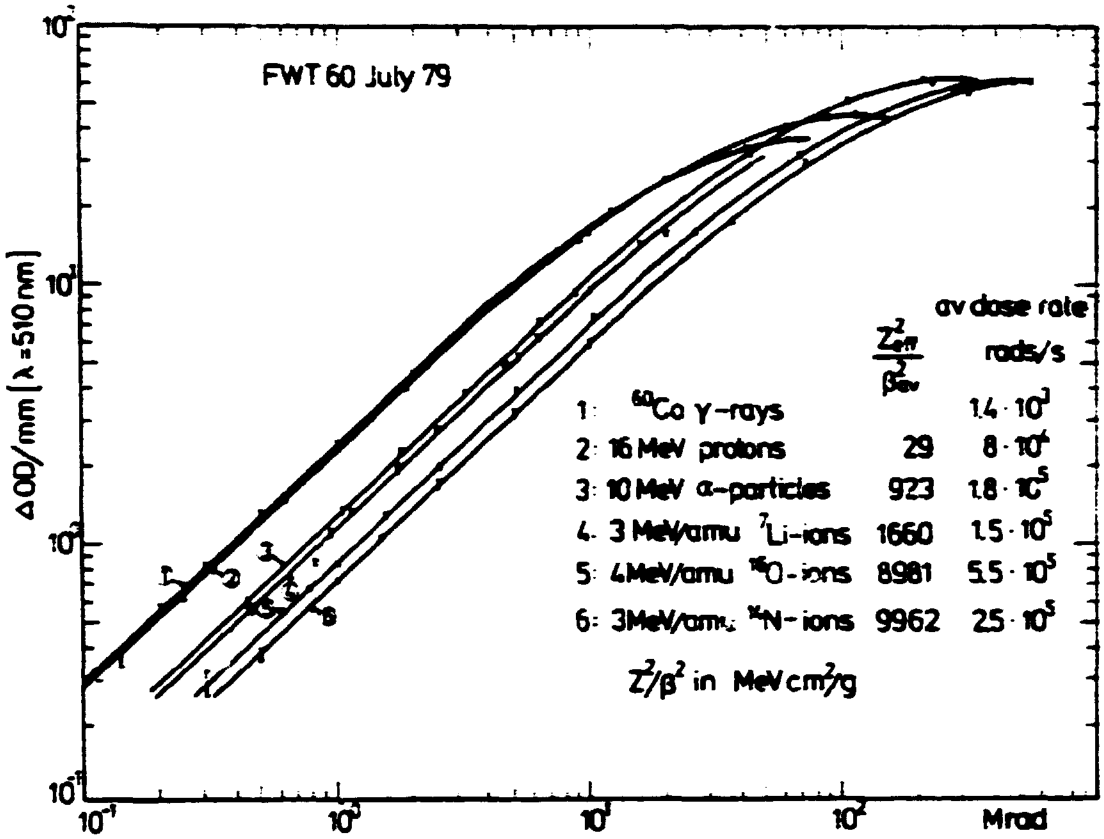

Fig. 4. Optical density of the thin-film detector versus dose. Experimental results for different radiation qualities.

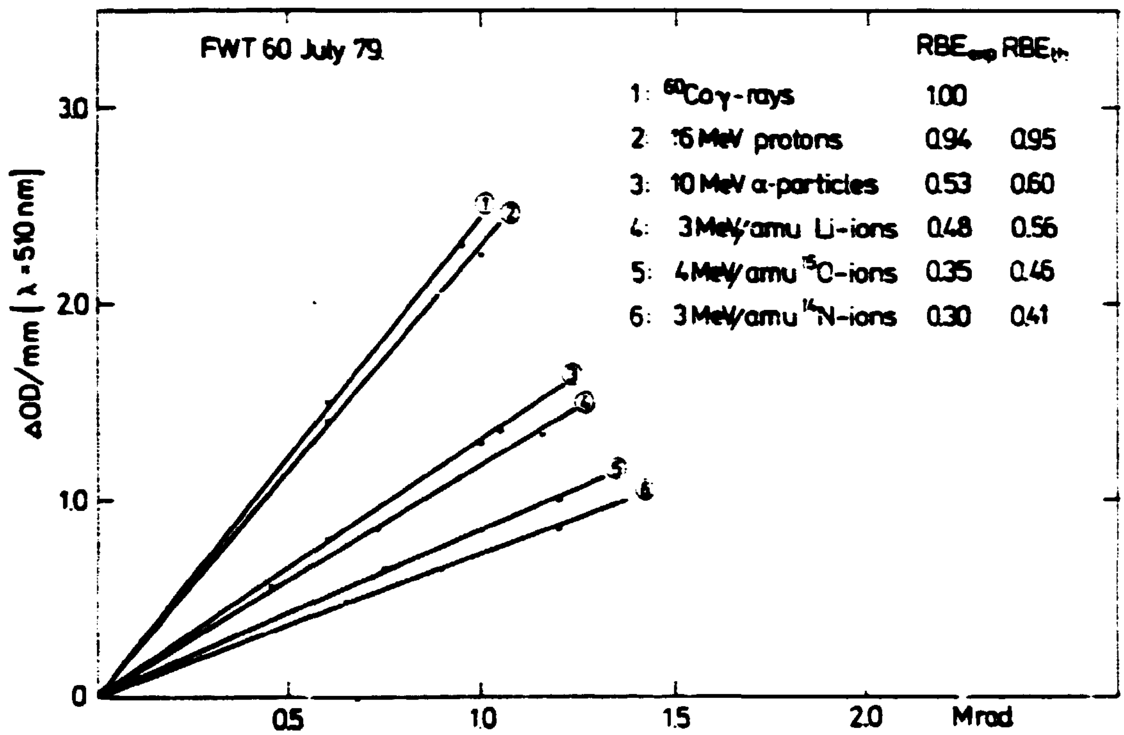

Fig. 5. The experimentally determined RBE values are found from the initial slope of the optical density versus dose. Comparison between experimental and calculated RBE values.

Risø National Laboratory | **Risø - M - 2308**

Title and author(s)

High-LET Dose-Response Characteristics Described by Track Structure Theory of Heavy Charged Particles.

Johnny W. Hansen and Kjeld J. Olsen*

*Department of Radiophysics
KAS Herlev
DK 2730 Herlev, Denmark

Date September 1981

Department or group

Accelerator

Group's own registration number(s)

14 pages + 1 tables + 5 illustrations

Abstract

The track structure theory developed by Katz and coworkers ascribes the effect of high-LET radiation to the highly inhomogeneous dose distribution due to low energy δ-rays ejected from the particle track. The theory predicts the effectiveness of high-LET radiation by using the ion parameters z_{eff}, effective charge of the ion, and $\beta = v/c$, the relative ion velocity, together with the characteristic dose D_{37} derived from low-LET dose-response characteristic of the detector and the approximate size a_o of the sensitive element of the detector. ^{60}Co gamma-irradiation is used as a reference low-LET radiation, while high-LET radiation ranging from 16 MeV protons to 4 MeV/amu ^{16}O-ions covering an initial LET range of 30-5500 MeVcm^2/g is obtained from a tandem Van de Graaff accelerator.

A thin film (5 mg/cm^2) radiochromic dye cyanide plastic dosemeter was used as detector with the characteristic dose of 16.8 Mrad and a sensitive element size of 10^{-7} cm.

Theoretical and experimental effectiveness, RBE, agreed within 10 to 25% depending on LET.

Copies to

Available on request from Risø Library, Risø National Laboratory (Risø Bibliotek), Forsøgsanlæg Risø), DK-4000 Roskilde, Denmark
Telephone: (03) 37 12 12, ext. 2262. Telex: 43116